The Fractal Behavior of Cloud Systems

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Abstract

The DOD and other agencies interested in cloud simulations have used fractal-based synthetic cloud generators since Lovejoy (1 982) showed the fractal behavior of clouds. Fractal generators are attractive because they allow simulations managers to control the synthetic cloud's statistical moments. One of the most appealing features of fractal methods is that simulated scenes can be produced at a variety of scales with just one number, the fractal dimension. This paper analyzes the temporal and spatial behavior of the fractal dimension of cloud fields of scale sizes from 1280 km to 10 km. The variations in the fractal dimension overtime and space will be shown to be significant and must be considered by the simulations community.

Introduction

Fractal scene generators create realistic looking clouds as the environmental backdrop for DOD weapons and exercise simulators. Realism, as an esthetic parameter judged by the human eye, may not be sufficient to produce simulated results whose output must reproduce results that mimic real-world scenarios. If the simulations scenarios are based on specific locations and times in the real-world, then the synthetic clouds should exhibit the same merm cloud coverage, structure, and gradients as the cloud climatologies. This paper represents the frost fractal analysis using the CHANCES database (Vender Haar, 1995). This 5-km, hourly, global database is ideal for generating the fractal dimension for large cloud fields. This study produced fractal dimensions for a massive data set which includes over 80 percent of the Northern Hemisphere for June and July of 1994. Approximately 1600 hourly 5-km cloud scenes of the Northern Hemisphere were used in this analysis.

Methodology and Data

The CHANCES database is described in a companion paper in the Conference Proceedings, Forsythe et al. (1997). Fractal analysis of clouds using this dataset is straightforward because the database is in a constant area molwede projection. The nature of the database, i.e. a 5-km, hourly, global coverage, makes it ideal to probe the fractal nature of large-scale cloud systems. Three specific scenes were analyzed for fractal dimension. These three scenes were created by using the IR images in the CHANCES dataset and thresholding the radiances for temperatures greater than 273,263 and 253 Kelvin, respectively. Because of the nature of the satellite geometry and retrieval, the 273 degree threshold cloud analysis contains all of the 263 scene and the 263 degree scene contains all of the 253 degree thresholded scene. These three closely spaced temperature threshold analyses were selected to investigate the multifractal or textural nature of the scenes.

We used the Box Counting method of fractal analysis as describe by Walsh and Watterson (1993). Each of the cloud/no cloud scenes generated by the three temperature thresholds were run against the box counting method. We selected an outside domain of 256 x 256 pixels or 1280 x 1280 kilometers. Larger domain sizes were "saturated" in that they provided no useful information since they invariably had at least one pixel filled with cloud.

Via box counting, the filled vs. Total domain size counts of the image were collected as the domain size was halved in both dimensions. A log-log plot was generated and a linear regression fit was applied to the points. The six data points that the linear fit was generated from were limited, like all box counting techniques, by the smallest (5 km) and largest (1080 km) scale sizes allowed by the data. The slope of the linear regression line defined the **fractal** dimension of the scene in question.

Data Domain

The CHANCES data, including all consecutive hours from June and July of 1994 was analyzed.

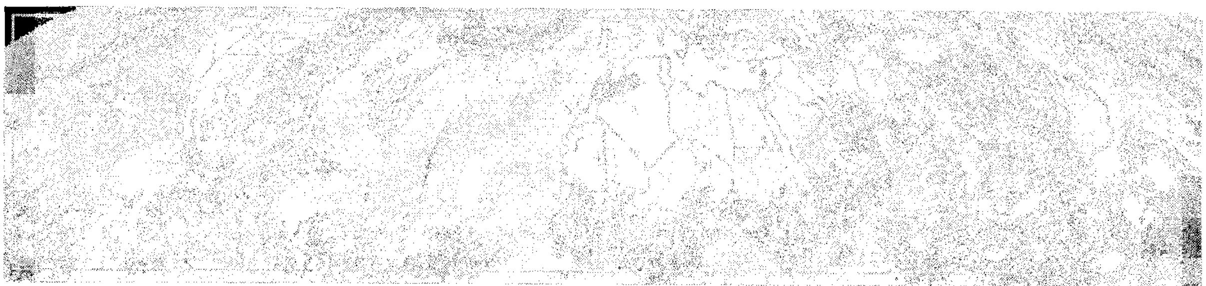

Figure 1 - CHANCES domain used in box-counting analysis

We selected most of the Northern Hemisphere **from** the equator to about 30 degrees north latitude for the region. Adj scent 256 by 256 pixel analysis domain boxes were created across this data domain.

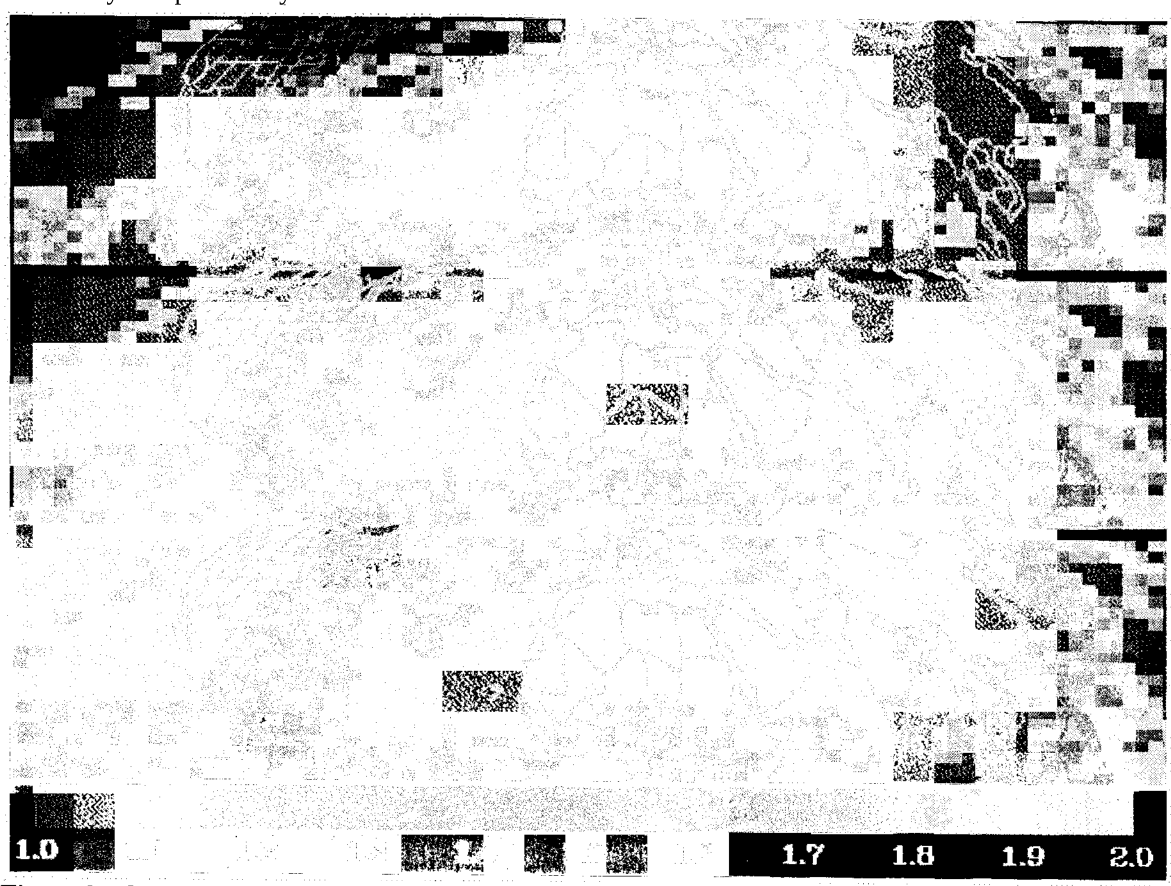

Figure 2 - Grayscale depiction of Fractal Dimension at 2[illegible] d 253 Degree Thresholds

Figure 2 shows the **fractal** dimension of the three temperature thresholds. Note that the blocks in the images are the 256 x 256 pixel domains of the box counting analysis. The gray scale indicates the **fractal** dimension. These three plates are simultaneous in time and the same time as the IR image in Figure 1. The difference at any pixel location between the three analyses is the **multi-fractal** texture. Black density depicts a **fractal** dimension of 1.0 or represents clear areas in the cloud analysis. One of the more interesting findings of this analysis was the strong dependence of the **fractal** dimension on the cloud cover percentage.

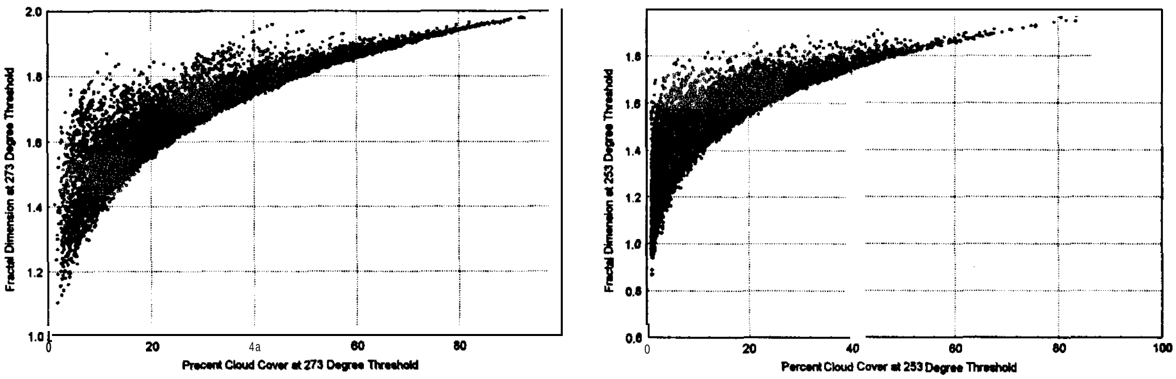

Figure 3- **Fractal** Dimension vs Cloud Cover Percentage all Data for 273 and 253 Degree Threshold Analysis

Figure 3 shows the **fractal** dimension vs. cloud cover for the 273 and the 253 degree threshold analyses. After inspection of the scatter diagrams, the scatter is predicable. At low cloud cover fractions, the satellite is more likely to detect multiple layers of clouds in different turbulence regimes in one scene. Also the degrees of freedom or the possible ways clouds can be structured are more numerous. Both of these possibilities are reflected in the high scatter of the **fractal** dimension on the low end of the cloud cover axis. On the other hand, as the scene approaches total cloud cover, the likelihood of a cloud shield obscuring lower level clouds increases and the satellite view is more likely to only see one turbulence regime associated with the top and obscuring layer of cloud. Additionally, the **fractal** dimension of a totally covered scene is always 2.0. Lower numbers are not possible so it stands to reason that high cloud cover fractions must approach 2.0 in **fractal** dimension and that the scatter must approach zero as the coverage approaches 100 percent.

Temporal Variations in Fractal Dimension and Multi-Fractal Values

Figure 4 shows a 500 hour consecutive time series of **fractal** dimension variation in a single domain along the central Florida coast starting on 22 June, 1994. Several features are worth comment:

1. As expected, the **fractal** dimension of the 273 degree threshold is always larger than the 263 degree threshold analysis which in turn is larger than the 253 degree threshold analysis. This is the result of the strong dependence on cloud cover which shares the same relative ranking.
2. There is a strong diurnal signal in the cloud cover and even a stronger signal in the **fractal** dimension.
3. The textural or **multi-fractal** signal, which is represented by the divergence in the **fractal** dimension between the three threshold values is strongly dependent upon cloud cover percentage with the most "texture" associated with the less cloudy periods.
4. The variation in **fractal** dimension and texture have similar temporal behaviors.

These conclusions are representative of all locations and times in the study domain.

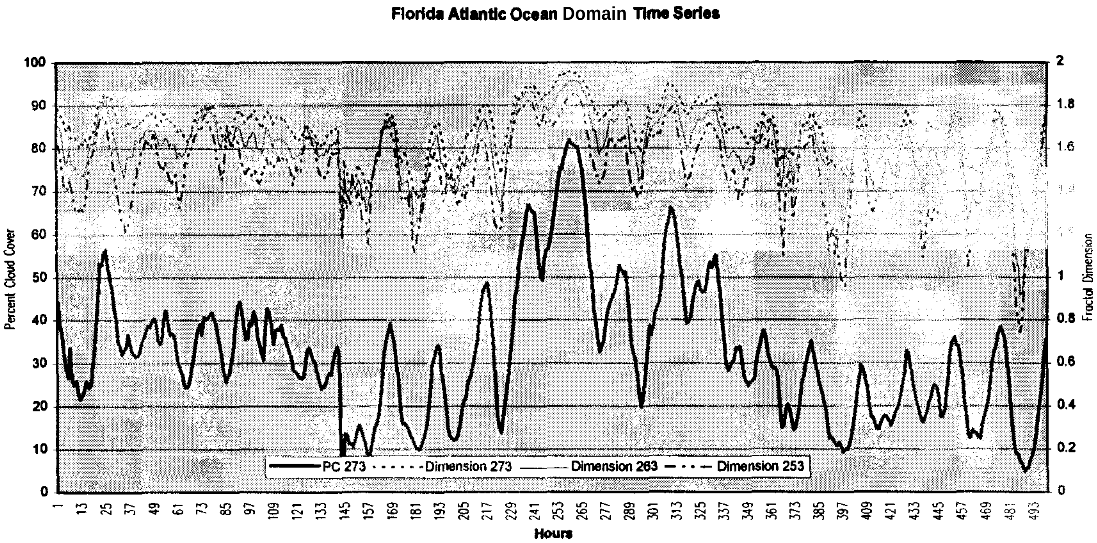

Figure 4 Time series of **fractal** dimension **for central eastern Florida coast**

Scale Break Considerations

The six data points generated by the Box Counting, and used to calculate the **fractal** dimension were also used to determine whether there was a scale break feature in the **fractal** domain. This was accomplished by filtering the data points for regression **fit** and assuming the data fit two different lines when the lower R^2 regression fits were observed. The subsequent R^2 for the two line regressions were again filtered to include only regressions of greater than 0.9999. This very high correlation thus assured that the two lines represented real **fractal** dimension values. The two lines were then solved for their intersection. This intersection represents the scale break in kilometers in the analyzed domain.

Figure 5 shows the histograms of scale break frequencies for the entire data set. The histograms are categorized in two different ways. First in standard 50 km cases and second, in 97 km cases. The 97 km bin was selected because it represents twice the RTNEPH's 47 km resolution. Many DOD researchers use the RTNEPH cloud analysis to generate **fractal** dimensional values. Often, **fractal** dimensions are extrapolated to smaller scales so cloud scenes at resolutions well below the resolution of the supporting data, can be generated in tactical and one-on-one simulators. This is acceptable if there is no scale break. As an example, if the Army is interested in a **fractally** generated cloud scene at the 5-km scale, and used a **fractal** dimension seed from the RTNEPH database, the artificial cloud would only be representative of real-world clouds if there was no scale break between 5 km and 97 km. If there were a break at these scale lengths, the **fractal** dimension of the correct cloud scene would be unresolvable by the **RTNEPH** database. The histograms indicate that there are scale breaks unresolvable by the **RTNEPH** approximately 50 percent of the time over most of the Northern Hemisphere. Our analysis misses another class of scale breaks entirely, i.e. scale breaks below **10** km where the CHANCES database is unable to resolve the **fractal dimension** change.

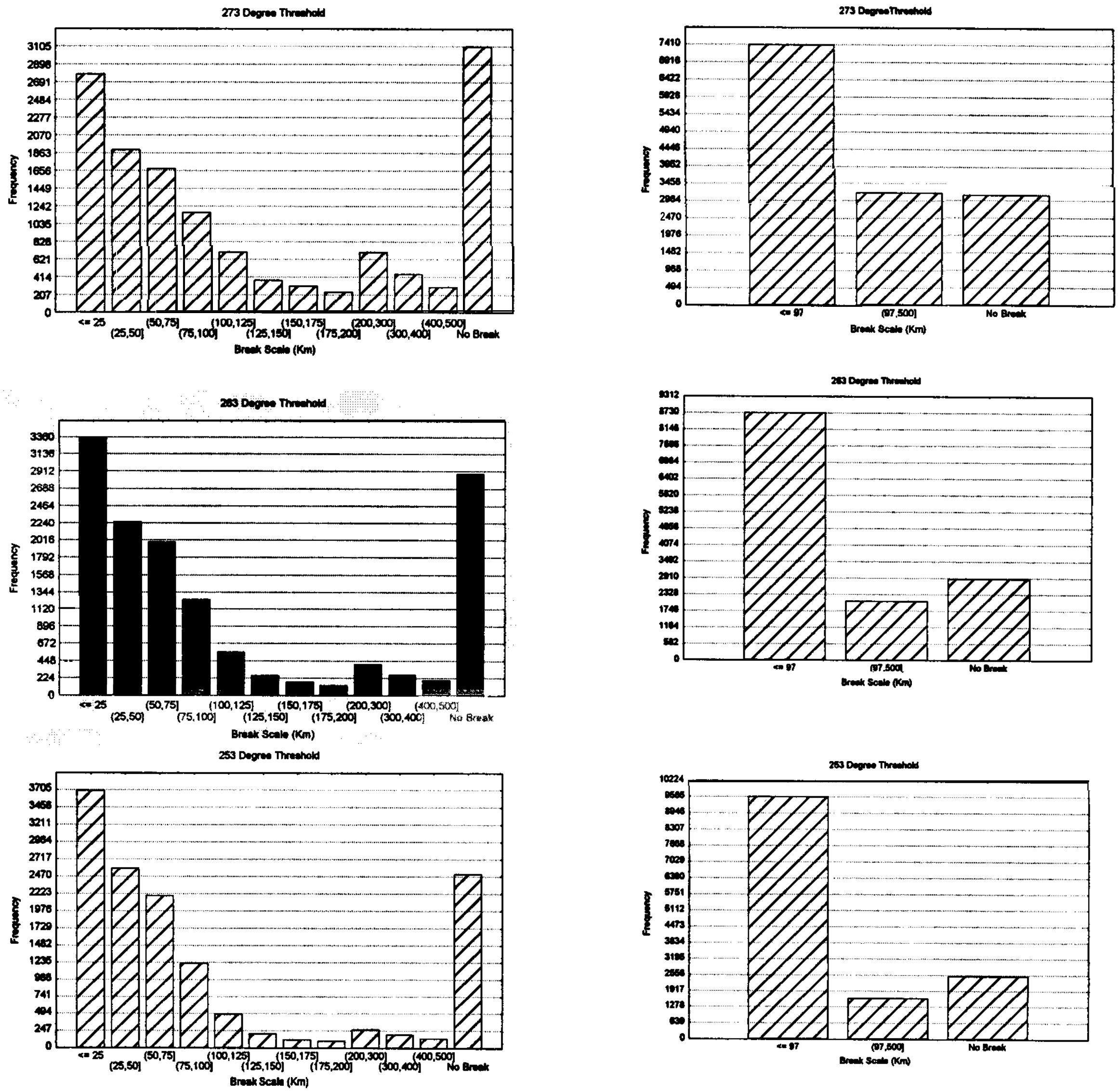

Figure 5 - Scale Break Histograms for July 1994 Northern Hemisphere

The Linear Regression Issue - Are All Cloud Fields Fractal?

The assumption in this paper and the opinion of many researchers is that clouds are fractal. Lovejoy's first paper showed an analysis with the data collected for a large cloud scene with the data falling amazingly close to a linear regression line. The question is how good a fit is required to be fractal. In preliminary studies we used the Box Counting method on simple geometrical objects. Objects such as a square are clearly not fractal because they do not conform to the basic requirement of self similarity at various scale sizes. Box Counting yields an R* regression fit of 0.9933 and a fractal dimension of 1.1346 for a square of 3 by 3 in a analysis domain of 8 x 8 pixels. Most researchers in the physical sciences would be quite happy with correlations of better than 0.9. Apparently, very high correlations do not necessarily imply fractal behavior. Figure 6 shows the breakdown of correlation coefficients for all of the Northern Hemisphere summer data. The data in the case bins less than 0.99 and between 0.99 and .995 are suspect in terms of their fractal behavior. Cloud features anchored to terrain or coastal features may not be treatable with fractal methods.

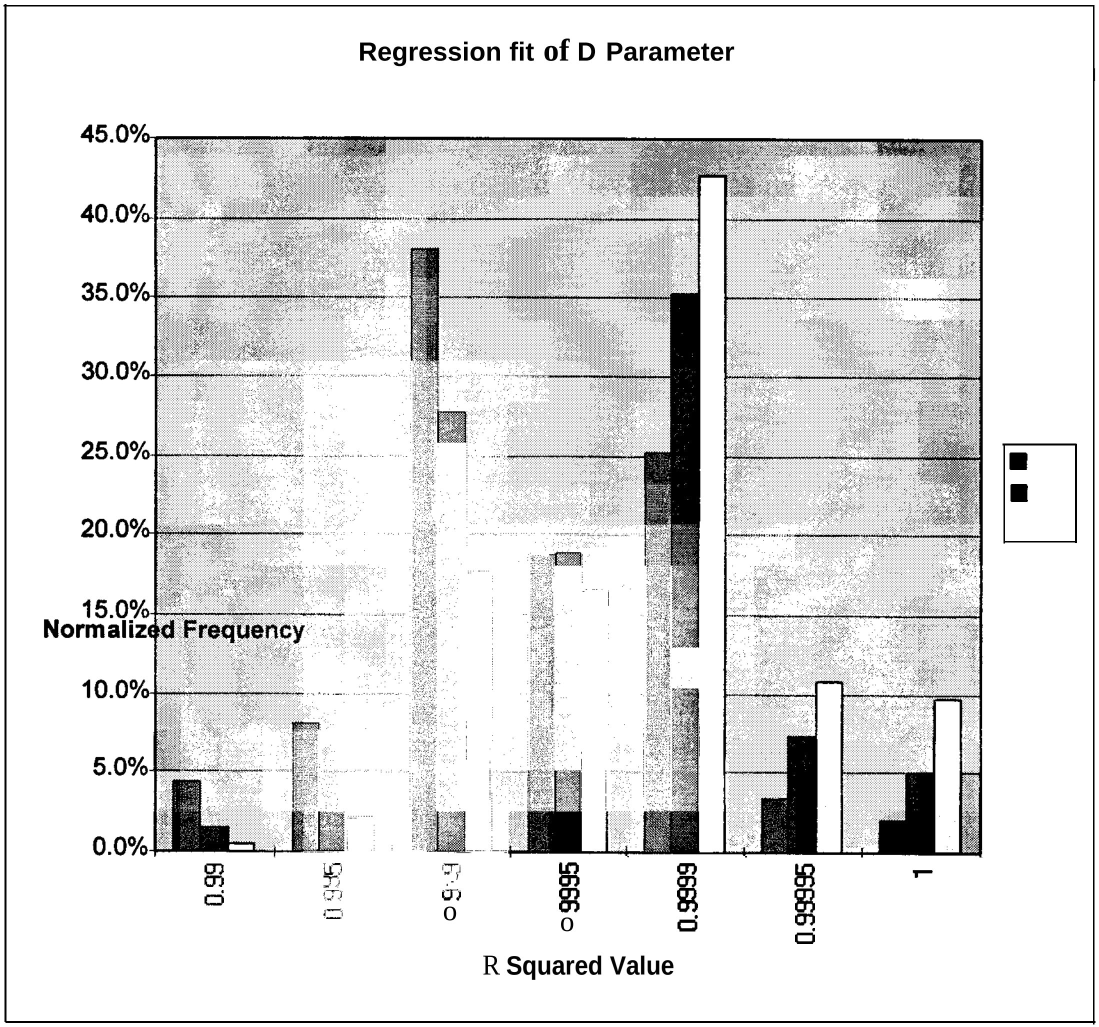

Figure 6 Histograms of Linear Regression Fit for all Analyzed Data

Conclusions

1. Large scale cloud features can in general be treated with **fractal** techniques.
2. The application of a given **fractal** dimension, generated at a given place and time must not be used at other locations or times. The temporal and spatial variation in the **fractal** dimension is too great to **assume** much representative spread in its use.
3. If **fractal** cloud scene generators are being used to yield extrapolated scenes with resolutions well below twice the resolution of the original data set, the **fractal** dimension used to seed the generator has at least a 50-50 chance of being in error. If the intent of the artificial scene is just to show a realistic looking cloud, there is no problem. If on the other hand, the intent is to create a cloud scene that represents the proper statistical moments of the real cloud climatology for a specific location and time, the result is likely to be wrong.

Variables for Northern Hemisphere	Number of Samples	Mean	Std. Deviation
Cloud % 273	13680	30.53	17.99
Cloud % 263	13680	21.68	15.07
Cloud % 253	3680	14.46	12.067
Fractal Dim 273	3680	1.687	.145
Fractal Dim 263	3680	1.61	0.162
Fractal Dim 253	3680	1.506	0.186
Variables for Florida Domain only	**Number of Samples**	**Mean**	**Std. Deviation**
Cloud % 273	961	29.26	14.67
Cloud % 263	961	21.48	12.68
Cloud % 253	961	15.22	10.42
Fractal Dim 273	961	1.654	0.143
Fractal Dim 263	961	1.567	0.174
Fractal Dim 253	961	1.472	0.211

Acknowledgments

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